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SAFETY IN MINING AND PROCESSING INDUSTRY AND ENVIRONMENTAL PROTECTION

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Determining airflow requirements in mine workings based on field measurements of actual emissions from internal combustion engine equipment

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Abstract

The increasing complex geological and hydrogeological conditions ore deposit mining, deeper excavation sites, and ambitious business expansion strategies, necessitate the use of high-performance, heavy-duty self-propelled machinery and winning equipment. Such activities significantly strain mine ventilation systems and demand innovative safety measures during mining.

This study assesses the influence of interconnected production variables on the aerological safety of mining operations. It provides real-world data on emissions from diverse sources within mines. The analysis includes an examination of current methodologies for estimating the air volume needed to dilute exhaust gases from diesel-powered machinery. Through numerical simulation that accounts for changes over time, the study was able to predict how exhaust gas concentrations would disperse within mines. These theoretical findings were then confirmed through empirical observations made in actual mining setting The field studies conducted, alongside their thorough analysis, underscored the necessity for adopting new, more sophisticated approaches to calculate airflow requirements in mines operating ICE machinery. A particular methodology developed by the MMI of the NUST MISIS (hereinafter referred to as the Methodology) was put forward as the primary tool for this purpose. The Methodology's precision and benefits were closely scrutinized, revealing its effectiveness in ensuring aerological safety in mines.

Keywords

mine, ventilation, exhaust gases, required airflow, internal combustion engine, rated exhaust, gas dynamics, numerical simulation, field tests

For citation

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Определение расхода воздуха в горных выработках на основе натурных измерений фактической газовости оборудования с двигателями внутреннего сгорания

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Аннотация

Все более сложные геологические и гидрогеологические условия отработки рудных месторождений, ведение работ на более глубоких горизонтах, а также амбициозные планы экономического развития предприятий поставили задачи использования высокопроизводительного, мощного дизельного самоходного и добычного оборудования. Это сказалось на увеличении нагрузки на вентиляционную сеть и потребовало использования новых методов обеспечения безопасности при ведении горных работ.

Приведена оценка влияния взаимосвязанных производственных факторов на аэрологическую безопасность рудника. Представлены фактические данные по газам, поступающим от различных источников. Проведен анализ метода расчета необходимого количества воздуха по фактору выхлопные газы дизельного оборудования. Проведено численное моделирование динамических процессов (с изменяющимися во времени параметрами), позволившее установить распределение концентраций выхлопных газов по горным выработкам. Последующие натурные измерения позволили верифицировать полученные результаты математического моделирования в условиях горных предприятий. Проведенные натурные эксперименты и их анализ позволили обосновать необходимость внедрения новых, более совершенных методов расчета расхода воздуха для рудника, использующего оборудование с ДВС. В качестве основного метода расчета требуемого количества воздуха использовалась методика, разработанная в МГИ НИТУ «МИСИС» (далее – Методика), были оценены ее точность и преимущества.

Ключевые слова

рудник, вентиляция, выхлопные газы, требуемый расход воздуха, двигатель внутреннего сгорания, норма выбросов, газодинамические процессы, численное моделирование, шахтные измерения

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Introduction

Advancements in mining technologies necessitate refined methodologies for estimating ventilation airflow per unit of diesel power, which emerges as a principal variable

Previous techniques (e.g.,[1]) failed to consider numerous determinants influencing the infiltration of pollutants from diesel vehicles into mine air. It is noteworthy that self-propelled diesel machinery constitute the primary source of air pollution in many mines. The prevailing analytical methods exhibited poor correlation with actual gas concentrations, often resulting in a substantial overestimation of the necessary fresh air flow.

The accuracy of airflow estimation stands at approximately 50%, a level of precision that detrimentally impacts mining operations.

To address this issue, evaluations were carried out at a facility managed by Yakovlev Mining and Processing Plant in 2021[2] aiming to assess the methodologies for analyzing the relationship between airflow and diesel engine exhaust emissions.

The approach developed by the Moscow Mining Institute[3] was enhanced through novel measurement techniques, designed to evaluate exhaust gas dynamics across varying vehicle loads.

The deployment of specialized instruments enabled the precise quantification of actual exhaust volumes and other relevant gas metrics over time. For this purpose, an array of specialized mine air analyzers was utilized, including APR-2, MBGO-2, TGO-2MP, APA-1, MRU Delta 2000 CD, Testo 350, Microsense M3), with all supplementary measurements adhering to established procedural standards.

The current practice of estimating required airflow does not differentiate between ore and coal mines[4], despite the distinctive patterns of exhaust gas emissions inherent to each type. Specifically, ore mines are characterized by significantly more extensive blasting operations [1, 2].

Self-propelled diesel machines and equipment are the main sources of exhaust and thermal emissions in mines, as well as technologies that use consolidating backfill [3–5]. The estimation of the requisite air volume in standard ore mines takes into account several critical factors: [1, 6, 7]:

– toxic fumes from blasting operations;

– toxic diesel exhausts;

[1] Federal Industrial Safety Code. Mining and Solid Minerals Processing Safety. Directive No. 505, Dec. 8, 2020.

Coal Mines Ventilation Design Guidelines. Moscow, Nedra Publishing, 1975.

Safety of Coal Mine Vehicles: Collected papers. Series 05 Issue 12. Moscow: Industrial Safety Research Center, Russian National Mining Safety Agency, 2004.

[2] Mine Air Flow Estimation Method and Ventilation Options. Research Report. Supervisor: S. Kobylkin, Doctor of Science (Engineering), MISIS Univ., 2021.

[3] Efficient Ventilation for Deep Mines with Diesel-Powered Equipment. Research Report. Supervisor: Prof. L. Puchkov, Doctor of Science (Engineering), 1976.

[4] Federal Industrial Safety Code. Mining and Solid Minerals Processing Safety. Directive No. 505, Dec. 8, 2020.

Coal Mines Ventilation Design Guidelines. Moscow, Nedra Publishing, 1975.

– toxic gases emanating from exposed rock and broken ore;

– dust content;

– heat emission;

– airflow needed for respiration, correlating with the number of individuals in the mine.

Among these, methods accounting for dust content and blast fumes are notably advanced, presenting minimal error in calculating needed air volumes [2, 8, 9]. Conversely, gases from ore and air for breathing, based on personnel count, are less impactful.

Operational experience in mines employing high-performance diesel equipment demonstrates that diesel exhaust gases are the critical factor in calculating the necessary air volume [5, 10].

Despite the long-standing use of diesel machinery in mining, a universally accepted standard for air quantity estimation to mitigate diesel exhaust effects remains elusive. The historical benchmark of a minimum 5 m^3/min per horsepower is still in use[5] [11].

Hence, the primary considerations for determining the air supply in mines are the toxic fumes from blasting and emissions from diesel machinery. Enhancing the precision and optimization of airflow estimation methods is vital for significantly reducing ventilation costs in mining operations.

The typical rate of fresh air supply to mines is in the order of hundreds of cubic meters per second. Inaccuracies in estimating the necessary airflow result in substantial losses. For instance, while an acceptable margin of error ranges from 15 to 20%, the actual volume of air delivered frequently surpasses the required amount by as much as 50%. Managing such a vast influx of air, and ensuring its distribution meets the specific requirements of each ventilated area, poses significant engineering challenges.

These issues underscore the need for innovative, modern analysis techniques. A particularly promising approach is one that adopts a more nuanced consideration of dust and exhaust sources within mines, especially focusing on the primary emission contributors: blasting operations and diesel-powered equipment [4, 6, 12].

The proposed method for air volume estimation, aimed at mitigating diesel exhaust impacts, significantly lowers ventilation costs by incorporating a comprehensive range of factors.

Materials and Methods

The Yakovlev Mining and Processing Plant operates a mine with complex ventilation ductwork, featuring numerous parallel and diagonal connections and requiring extensive air gate control. The mine's challenging geology and its location in a densely populated area add layers of complexity, complicating efforts to maintain optimal mine air conditions such as temperature, humidity, and safety, especially considering the diminished oxygen levels and the presence of toxic fumes from blasting and internal combustion engines [12, 11].

These factors impact the air's humidity, temperature, and absolute pressure.

Experimental air quality assessments in the mining work areas identified the primary sources of hazardous gases and dust in underground mines as follows:

– blasting;

– diesel equipment;

– oxidation;

– mineral extraction production processes.

These activities release toxic substances like carbon monoxide, nitrogen oxides, acrolein, and formaldehyde, posing risks to human health, including respiratory issues [12].

To evaluate the mine's ventilation efficiency, we compared actual and required airflow rates and analyzed the composition and volume of internal combustion engine (ICE) exhaust emissions under various conditions.

Our numerical estimates were cross-verified with direct field measurements of air properties within the mine and the mine ventilation system's (MVS) performance, including regular monitoring of hazardous pollutants in the mine air. The South and Center Region Paramilitary Mine Rescue Team's Test Lab analyzed the exhaust gas's composition, volume, temperature, and air quality near the self-propelled diesel equipment.

In addition to increased levels of harmful gases and dust in the work area's air, mines also face harmful physical factors such as heat emissions, originating from equipment and stowing operation[6] [9].

The assessment of thermal impacts included applying thermal imaging principles in mines to analyze heat emissions from the operation of machinery and equipment.

[5] Coal Mines Ventilation Design Guidelines. Moscow, Nedra Publishing, 1975.

Safety of Coal Mine Vehicles: Collected papers. Series 05 Issue 12. Moscow: Industrial Safety Research Center, Russian National Mining Safety Agency, 2004.

[6] Mine Air Flow Estimation Method and Ventilation Options. Research Report. Supervisor: S. Kobylkin, Doctor of Science (Engineering), MISIS Univ., 2021.

The investigation into the underground mine's microclimate revealed that fresh air, differing in temperature from the surrounding rocks and in gas composition from the outgoing air, flows into the mine.

Furthermore, exhaust gases, with temperatures between 40 to 370 °C, additionally heat the mine's atmosphere.

The concentration of toxic gases in the ICE exhaust was measured by analyzing both the standard samples taken regularly and express analyses used to determine the composition of undiluted exhaust under various loads of the ICE-driven equipment. Both steady-state and transient engine operations were studied.

The required amount of air to offset the above factors was estimated using the actual exhaust emissions of the existing equipment. The actual exhaust volume was determined as a function of the maximum fuel consumption and concentrations of all toxic gases. This volume was then used to calculate the amount of air required to dilute the toxic gases to the maximum allowable concentration (MAC) for each type of equipment.

The engine was started, and its rpm in steady and transient operations under various loads as the equipment performed its typical duty was recorded. The measurement results, gas emission rate vs. time, and exhaust gas temperatures are shown in Fig. 1.

Based on the actual exhaust measurements, a method for estimating air consumption in mines with ICE equipment was developed[7].

Estimation of the Amount of Air Required to Dilute Toxic ICE Exhaust Gases

The volume of fresh air supplied to areas of the mine where ICE equipment operates, either continuously or intermittently, must be adequate to dilute the primary toxic components of the exhaust gas (specifically carbon monoxide and nitrogen dioxide, assessed in NO_2 equivalent) to maximum allowable concentrations or to maintain the prescribed oxygen levels. This volume is calculated as follows:

$$Q_{ICE} = k_{para} \sum k_{duty} Q_{eq}, \ \text{m}^3/\text{s}, \quad (1)$$

where k_{para} is the factor for parallel operation of multiple ICEs at the same location, with k_{para} = 1.0, 0.9, 0.85 for the simultaneous operation of 1, 2, 3, or more engines within the same ventilation system segment; k_{duty} is the ICE duty cycle factor, reflecting the proportion of time the vehicle spends at the location relative

[7] Mine Air Flow Estimation Method and Ventilation Options. Research Report. Supervisor: S. Kobylkin, Doctor of Science (Engineering), MISIS Univ., 2021.

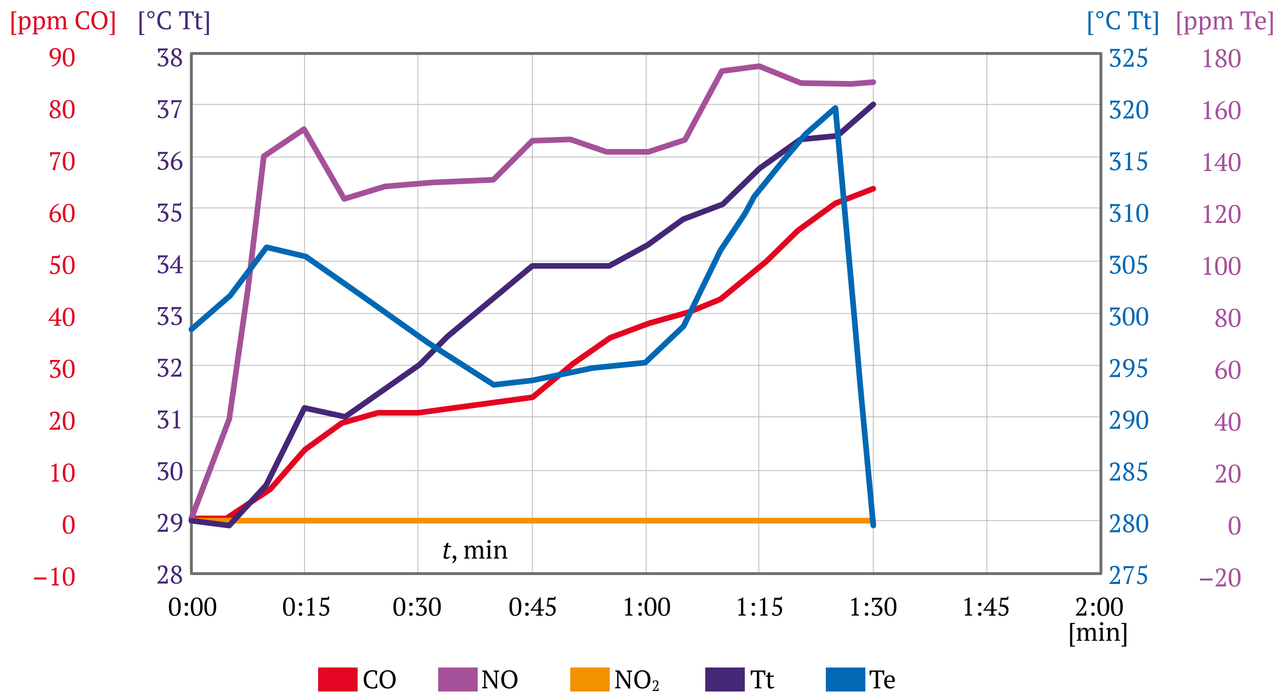

Fig. 1. Composition and Temperature of Exhaust Gases at Engine Idle: time-dependent concentrations of carbon monoxide (CO), nitrogen oxide (NO), and nitrogen dioxide (NO_2), ppm; ambient temperature (Tt) and exhaust gas temperature (Te) over time, °C; t is time, min

to the entire cycle time, ranging from 0.1 to 1; Q_{eq} is the volume of air needed to ventilate each ICE, m³/s.

The duty cycle factor is defined as

$$k_{duty} = \frac{t}{t_c}, \qquad (2)$$

where t is the duration of ICE operation at the specifed location, min; t_c is the equipment cycle time, min.

Air consumption required to neutralize each exhaust gas component is calculated as

$$Q_m = \frac{c_{out}}{c_{MAC}} g_{out}, \text{ m}^3/\text{s} \qquad (3)$$

where c_{out} is the concentration of toxic exhaust components (maximum concentration of nitrogen oxides in NO_2 equivalent in undiluted engine exhaust), % vol.; c_{MAC} is the MAC of the component, % vol.; g_{out} is the flow rate of purified exhaust gas, m³/s.

Ehe quantity of exhaust gases is assessed based on direct measurements. For self-propelled diesel machinery used within the mine, the amount of exhaust emissions is established from the actual figures presented in Table 1.

When calculating the required ventilation flow, emissions from diesel-driven drilling equipment used in conjunction with other self-propelled diesel vehicles, as well as machinery used for secondary operations that do not operate continuously for more than 10 min within an hour or 40 min per shift, are not considered.

The findings highlighted consistent trends in how exhaust gases spread throughout the mine's spaces, irrespective of the mining technology applied. The positioning of the exhaust pipe plays a crucial role in influencing gas movement, with the highest concentrations of exhaust gases found in areas close to the pipe. Dynamic simulations facilitated the analysis of time-related changes in gas distribution, the visualization of airflow dynamics, and the assessment of gas dispersion metrics within the mine.

Research and analysis provided an average overview of the time allocated to production tasks and the rate at which gases are emitted from the main toxic elements found in exhaust gases.

The highest emission rates are confined to specific periods within the shift, not spanning the entire duration. This fact is vital for accurately calculating the volume of air needed for adequate ventilation.

Such precision enables the determination of the essential volume of fresh air for the mine when using ICE equipment, factoring in the actual volume of harmful emissions as the primary source of pollution. By analyzing the levels of toxic contaminants, it is feasible to set a ventilation standard for the use of ICE machinery, considering the machinery's power, operational conditions, and type, specific to each mine.

Table 1

Actual toxic gas concentrations, exhaust gas volumes from load haul dumpers (LHD), and estimated air quantity for maximum gas emission

LHD name	Engine power, N		Purified exhaust gas volume g_{out}	Toxic exhaust component concentration c_{out} CO	Maximum allowable concentration c_{MAC} CO	Maximum allowable concentration c_{out} NO_x	Toxic exhaust component concentration nox (total nitrogen oxides) c_{MAC} NO_x	Air consumption to offset Q_m CO	Air consumption to offset Q_m NO_x	Rated specific air consumption per LHD
	kW	h.p.	m³/s	mg/m³	mg/m³	mg/m³	mg/m³	m³/s	m³/s	m³/min per 1 h.p.
Caterpillar CAT R1300G	123	165	0.077	79.68	20	476	5	0.3	7.3	2.7
SANDVIK LH307	160	215	0.060	925	20	837	5	2.8	10.0	2.8
Sandvik LH410	235	315	0.175	73.81	20	315	5	0.6	11.0	2.1
EPIROC ST1030	186	249	0.059	48.4	20	412	5	0.1	4.9	1.2
Caterpillar CAT R1300G	123	165	0.077	79.68	20	476	5	0.3	7.3	2.7
SANDVIK LH307	160	215	0.060	925	20	837	5	2.8	10.0	2.8
Sandvik LH410	235	315	0.175	73.81	20	315	5	0.6	11.0	2.1
EPIROC ST1030	186	249		0.059	48.4	20	412	5	0.1	4.9

Note: the NO_X concentration is in the NO_2 equivalent = 1.53 NO + NO_2.

This standard is not a one-size-fits-all for the mining sector, as evidenced by international practices [9].

Numerical simulations of how exhaust gases disperse under different ventilation conditions revealed that an increase in airflow velocity (or flow rate) significantly shortens the exhaust gas dilution period. This enhancement also hastens the evacuation of gases from the mine.

When ventilating at the maximum allowable velocity, the concentration of gases is reduced by 3.5 times compared to the concentration observed when ventilating at the lowest airflow velocities.

Conclusions

Real-world emission data from self-propelled machinery show that different types of equipment emit varying levels of gases, and even within the same type of machinery, the concentration of harmful gases can differ. Interestingly, more powerful machines do not necessarily produce more harmful emissions. Additionally, it has been found through experiments that an increase in engine revolutions per minute (rpm) does not invariably lead to higher concentrations of exhaust gases.

These findings have informed the setup of initial and boundary conditions for computational modeling. Dynamic numerical modeling, which accounts for changes over time, indicates that the concentration of exhaust gases from ICE machinery tends to even out throughout the mine over time. The leveling of gas concentrations occurs approximately 100 meters from the emission source (exhaust pipe). Furthermore, an increase in the velocity of airflow markedly reduces the time required for the dilution of exhaust gases, thereby speeding up their removal from the mine. At the highest allowable airflow velocity, gas concentrations are diminished by 3.5 times compared to levels observed when air is circulated at the minimum allowable speed.

When multiple ICE machines are operated simultaneously in separate entries of a single mining block, the combined exhaust gases merge into the main ventilation passageway of the mine. In scenarios where ventilation is conducted sequentially, there's a possibility that some exhaust gases might flow into other active mining areas. This factor needs to be carefully considered in the design of ventilation schemes.

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